

ERRORS IN DETERMINING THE THERMAL CHARACTERISTICS OF LIQUIDS BY THE LASER-PULSE METHOD

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Abstract. The analysis of test conditions of determining the thermal diffusivity of liquids by the laser pulse method are analyzed. Numerical solution of the nonstationary temperature pattern of three-layer sample when exposed to the surface of the thermal pulse of high power and low time span problem was found. The limits of the range of possible changes in the value of the heat transfer rate to the heating surface, corresponding to the conditions of reliable determination of the thermal diffusivity of a typical organic liquid ethanol without changing its phase state was determined.

1 Introduction

Organic liquids are increasingly used in various fields of science and technology. It used as solvents[1], coolant-cutting fluids [2] and high temperature fluids [3]. Every year, new organic liquids are developing for special purpose of machinery and technology [4–5]. Thermal processes in the technical fluids and its thermal characteristics plays an important part in reliability control and normal operation of technical systems.

For these reasons, determination of the thermal characteristics with high accuracy becomes more actual task, especially in the development of new products and technical systems.

To investigate the thermal properties of such materials, it is best to use highly efficient procedures, for example, the laser pulse – laser flash (LFA) method [6, 7]. It is based on the absorption of a pulse of radiant energy in a thin layer by the frontal “hot” surface of the sample and the approximate solution of the one-dimensional heat conduction problem for an infinite plate. From the time-temperature dependence of the reverse (“cold”) surface of the sample, one can determine the maximum heating temperature T_{\max} and the time $\tau_{0.5}$ for half the maximum heating temperature of the cold surface of the sample to be attained.

The thermal diffusivity a of the material being investigated when using LFA method, is calculated as

$$a = 0.1388 \cdot L^2 / \tau_{0.5}, \quad (1)$$

where L is the thickness of the sample.

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If thermal diffusivity is known, the specific heat capacity c , and the thermal conductivity λ of the material can be calculated by formulas from [6,7]. The practical interest is the use of LFA method to determine the thermal diffusivity of organic liquids.

For materials that are solid determination of their thermal characteristics is not straightforward. For liquids this task becomes complicated by the necessity of creation of the measuring cell providing intensive heating of a uniform and plane-parallel layer of liquid of the known thickness. For this reason, the task of determination of the thermal characteristics of the liquids is divided to two tasks. The first task is providing the conditions of heating corresponding to the fundamental principles of LFA method (small duration and high intensity of heating) without liquid boiling up. The second task is by selecting the measuring cell layer thicknesses required to provide reliable determination of thermal characteristics, the temperature rise to "cold" surface layer of high thermal conductivity material used to make the measuring cell [8–11].

The design of the measuring cell is mainly determined by the equipment used for research thermal characteristics of materials. For example, measurement cell of laser flash analyzer LFA- 457 is a thin-walled metal cylinder (with a cover), which is placed under investigation liquid. The laser pulse is applied to the bottom of the measuring cell, temperature registration is carried out infrared sensor on the opposite side [12].

Exposure to high heat fluxes $q = 10^7 \dots 10^9 \text{ W/m}^2$ should lead to an increase in surface temperature (T_p) of the substance. Heating of the measuring cell surface by a laser with rate of heat transfer $q = 10^7 \dots 10^9 \text{ W/m}^2$ increase in surface temperature (T_p) of the test fluid.

The range of T_s is limited by the organic liquids initial boiling point, which for the majority liquids is 350...390 K [13]. This condition requires a limitation in the rate of heat transfer during experiment. During the heating of the measuring cell by a laser pulse, the temperature of the liquid surface may excess initial boiling point. This fact significantly reduces the accuracy of the thermal diffusivity of the test substance. For this reason, the magnitude of the pulsed rate of heat transfer must be limited to values of the temperature in any point of the layer of liquid below its boiling point.

The purpose of this work is analysis of the conditions determining the thermal characteristics of organic liquids by a laser pulse method.

2 Statement of the problem

To solve the problem of determining the thermal characteristics of organic liquids was used mathematical model from [14 –16] and one-dimensional Thermal Conductivity method for a three-layer infinite plate with constant rate of heat transfer q , pulse duration τ_{imp} and the absence of heat exchange with the environment.

In case of a problem definition it was supposed that the transverse size of the measuring cell is many times more liquid layer thickness can not be taken into account a possible two-dimensional heat-transfer process and heating due to the heat on the side walls of the cylindrical body.

Also, it was supposed, that thermal characteristics of the materials of the measuring cell and organic liquid do not depend on temperature. This assumption is justified for many materials in real-rated range of possible changes in temperature during the experiments even at high values of the heat flux to the on-heated surface of the sample due to the short pulse duration.

The problem is solved in a Cartesian coordinate system. Solutions represent a three-layer plate total thickness L_3 (fig. 1). Surface segment $x=0$ was heated by the energy pulse q . The pulse duration is τ_{imp} .

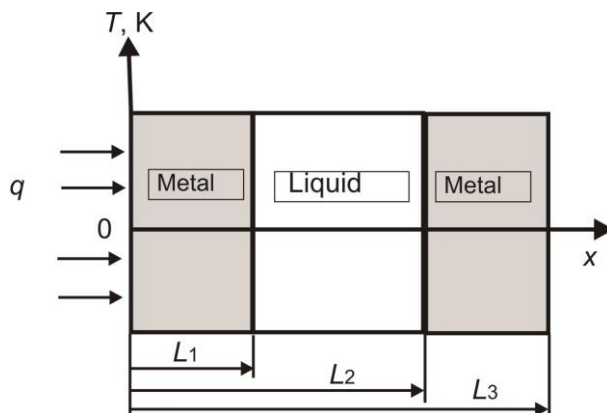


Fig. 1. Scheme of the area of solution.

The mathematical model consists of the three nonstationary heat equation

$$c_1 \rho_1 \frac{\partial T_1}{\partial t} = \lambda_1 \left(\frac{\partial^2 T_1}{\partial x^2} \right), \quad 0 < x < L_1 \quad (2)$$

$$c_2 \rho_2 \frac{\partial T_2}{\partial t} = \lambda_2 \left(\frac{\partial^2 T_2}{\partial x^2} \right), \quad L_1 < x < L_2 \quad (3)$$

$$c_1 \rho_1 \frac{\partial T_3}{\partial t} = \lambda_1 \left(\frac{\partial^2 T_3}{\partial x^2} \right), \quad L_2 < x < L_3 \quad (4)$$

with boundary conditions:

$$x = 0: \quad -\lambda_1 \frac{\partial T_1}{\partial x} = q, \quad \tau_{\text{imp}} > t > 0; \quad (5)$$

$$x = 0: \quad -\lambda_1 \frac{\partial T_1}{\partial x} = 0, \quad t > \tau_{\text{imp}}; \quad (6)$$

$$x = L_1: \quad T_1 = T_2; \quad -\lambda_1 \left(\frac{\partial T_1}{\partial x} \right) = -\lambda_2 \left(\frac{\partial T_2}{\partial x} \right) \quad (7)$$

$$x = L_2: \quad T_2 = T_3; \quad -\lambda_2 \left(\frac{\partial T_2}{\partial x} \right) = -\lambda_1 \left(\frac{\partial T_3}{\partial x} \right) \quad (8)$$

$$x = L_3: \quad \lambda_1 \frac{\partial T_3}{\partial x} = 0, \quad t > 0; \quad (9)$$

$$t = 0: \quad T_1 = T_2 = T_3 = T_0, \quad (10)$$

where ρ is the density of the material; q is a rate of heat transfer at the surface; T, T_0 are the actual and initial temperature; t is the time; subscripts 1, 2 are referred relate to the material of the measuring cell and the liquid.

3 Solution method

The above nonlinear boundary value problem was solved by the method of finite differences [17] using an iterative algorithm [18, 19], developed for the numerical solution of high-temperature heat-transfer problems in regions with local energy sources.

Problem (2)–(10) belongs to the category of singularly perturbed problems [20]. This problem is more complicated than those problems in [14–16]. The main difficulty of this task is the necessity of solving a system of three heat equations with a significant (hundreds of times) difference of materials heat diffusion of each layer.

In this case, to reduce the heat retention of the process, the metal plates (1) and (3) heat diffusion must be maximized. The heat diffusion of the organic liquids do not exceed $0.65 \text{ W/(m}\cdot\text{K)}$ [13]. Therefore, the numerical solution of heat diffusion problem for three-layer infinite plate with significantly different coefficients of thermal conductivity in a high-intensity pulsed heating is independent problem. Its solution is largely due to the choice of grid parameters. Therefore, the difference grid time steps chosen similarly to [11, 12] from 10^{-5} to 10^{-12} s.

The values of heat transfer rate and pulse duration taken in accordance with the actual possible characteristics of the laser source of identification of thermal properties of materials research apparatus. These conditions comply with the parameters of the laser source of modern quantum optical generator [21]: heat transfer rate $q = 10^7 \dots 10^8 \text{ W/m}^2$, pulse duration $\tau_{\text{imp}} = 0.1 \dots 2 \text{ ms}$ and emission wavelength 1.06 mkm .

4 Results and discussion

In [14–17] was found, that in determining thermal characteristics of solid materials by laser pulse method there is methodological errors caused adopted in formulating the problem [6, 7] assumptions. The errors in determining the thermal characteristics of material can be defined [14–16] by comparison of the actual values of thermal diffusivity (a) with the material obtained by numerical simulation of the implementation conditions of experiments on determination of thermal characteristics materials by this method. The errors of liquids thermal conductivity are determined by the method specified in [14–16].

The verification of the reliability of estimates numerical simulation was made temperature pattern of yogurt calculation (layer thickness of 1 mm , $\lambda = 0.267 \text{ W/(m}\cdot\text{K)}$, $c = 1600 \text{ J/(kg}\cdot\text{K)}$,) [11], located in the copper measuring cell with wall thickness of 0.5 mm ($\lambda = 110 \text{ W/(m}\cdot\text{K)}$, $c = 380 \text{ J/(kg}\cdot\text{K)}$, $\rho = 8530 \text{ kg/m}^3$) [11], rate of heat transfer was $q = 2.4 \cdot 10^7 \text{ W/m}^2$, a pulse duration was 1.5 ms , $T_0 = 273 \text{ K}$.

Grid time steps was not above $1 \cdot 10^{-6} \text{ s}$. The initial step in the coordinate $x = 5 \cdot 10^{-7} \text{ m}$, and in the areas near the borders of the materials chosen irregular (the algorithm of geometric series) [22]: $x_{i+1} = q \cdot x_i$, where q - coefficient of variation. At the boundary surface the step of simulation was decreased, and after crossing boundary surface it was increased. The coefficient of variation has been assumed constant ($q = 0.02$).

The difference between calculation and experience-based data [11] was about 0.2% . This confirms the accuracy of the numerical simulation results.

The thermal characteristics was calculated for the organic liquids in table 1 [13]. It was supposed, that the measuring cell was made from iron with wall thickness 0.5 mm ($\lambda = 20 \text{ W/(m}\cdot\text{K)}$, $c = 551 \text{ J/(kg}\cdot\text{K)}$, $\rho = 7894 \text{ kg/m}^3$) [23]. The parameters of the laser heating and the initial temperature selected like in the same problem in [11].

Table 1. Thermal characteristics of organic liquids [13].

Liquid	$C,$ J/(kg·K)	$\lambda,$ W/(m·K)	$\rho,$ kg/m ³	$a,$ m ² /s	$T_k,$ K
Water	4183	0.60	998.2	$1.4 \cdot 10^{-7}$	373
Methylbenzen	1630	0.139	885.5	$9.6 \cdot 10^{-8}$	383.6
Ethanol	1909	0.172	812.1	$1.1 \cdot 10^{-7}$	351.4

The disadvantages of the method [6, 7] is the assumption of an infinite magnitude of the heat transfer rate of the laser radiation to the heated surface. In practice, this value cannot be infinite. On the other hand, heating of the liquid by the laser with heat transfer rate $10^7 \dots 10^8 \text{ W/m}^2$ can lead to its boiling. This fact can greatly increase the error in determining the thermal diffusivity. For example, the boiling point T_k of Methylbenzene is 383.6 K, for Ethanol its 351.4 K [13]. The last condition requires limitation of the heat transfer rate in the experiment at the borders of measuring cell – liquid.

At the fig. 2 is shown the temperature distribution $T(x)$ in the Methylbenzene layer thickness 1 mm with a pulse duration 1.5 ms, the magnitude of the heat transfer rate $2.4 \cdot 10^7 \text{ W/m}^2$, depending on the duration of the heating period

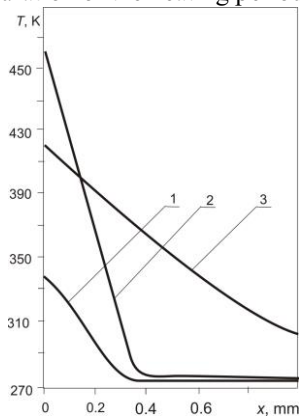


Fig. 2. The temperature distribution $T(x)$ in the Methylbenzene layer thickness 1 mm with a different pulse durations: 1 – 1.5 ms; 2 – 100 ms; 3 – 1 s.

From fig. 2 it is seen that at the time after pulse ending on the borders of the materials L_1 the liquid temperature varies and reaches its maximum 457 K at $t = 100 \text{ ms}$. This fact can be explain, that in conditions of low heat diffusion of the organic liquids heat energy accumulated in the material of the steel wall of the measuring cell after the laser pulse, and flows into the liquid, respectively, the temperature of a thin boundary layer increases. Then, the heat flow to the deeper layers of the liquid and the temperature is decreasing.

Simulations have shown necessity of substantial reduction of limit values (maximum) heat flows to determine liquids heat diffusion with thermal conductivity by the pulse method. In cases, when the wall thickness of the measuring cell is 0.5 mm, a liquid layer is 1 mm and the length of the pulse laser heating is $\tau_{\text{imp}} = 1.5 \text{ ms}$, the maximum allowable heat flow is as follows: water $1.35 \cdot 10^8 \text{ W/m}^2$; Methylbenzene – $5.84 \cdot 10^7 \text{ W/m}^2$; for ethanol – $4.5 \cdot 10^7 \text{ W/m}^2$.

The numerical results of heat diffusion of the liquids at a value of heat flux $2.4 \cdot 10^7 \text{ W/m}^2$ and $\tau_{\text{imp}} = 1.5 \text{ ms}$ are given in table 2.

Calculations show the possibility of determining heat diffusion of organic liquids by typical LFA method without its boiling with minimal errors.

Table 2. The numerical results and reference values of the heat diffusion of three types of liquids.

Liquid	a (lookup value), m^2/s	a (calculated value), m^2/s	Definition error, %
Water	$1.4 \cdot 10^{-7}$	$1.28 \cdot 10^{-7}$	0.34
Methylbenzene	$9.6 \cdot 10^{-8}$	$9.5 \cdot 10^{-7}$	0.9
Ethanol	$1.1 \cdot 10^{-7}$	$1.11 \cdot 10^{-7}$	0.28

5 Conclusion

In this work was shown possibility of determining the heat diffusion of organic liquids by the laser pulse method. Also, the parameters of the laser pulse, in which such determination is possible was defined. Analysis of systematic errors in the method and comparison of literature data with the results showed that the error is less than 1 %.

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